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Assessment on slag based geopolymer concrete blended with industrial waste using different ratios of alkaline liquid to binder and $NaOH/Na_2SiO_3$

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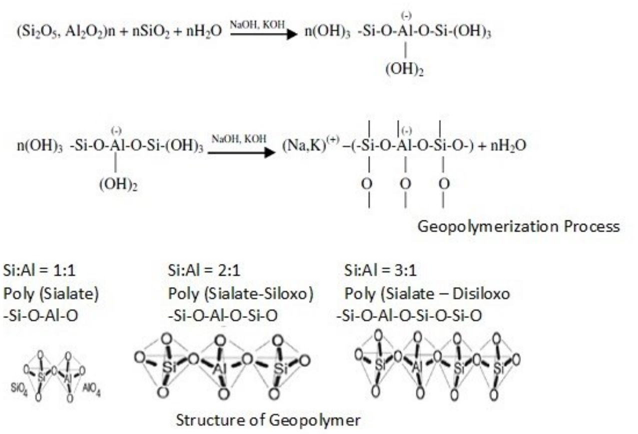
Graphical abstract



Abstract

At recent days, the rapid rate of increase in population and industrial growth generates enormous volume of waste products that creates environmental and health hazards. The production of cement is one of the key factors in liberation of CO_2 gases in atmosphere. The utilization of waste products not only eliminate the disposal problems but also reduces the emission of greenhouse gases to the atmosphere. This is one of the main reasons in developing slag based geopolymer concrete which leads to development of ecofriendly environment. This paper dealt with the suitability of Geopolymer Concrete by curing under ambient temperature for its adaptability in construction industry and the effect of different alkaline liquid to binder ratio such as 0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0,1.1, and1.2. And with different $NaOH/Na_2SiO_3$ ratios as 2,2.25 and 2.5. Experimental results were compared with various regression equations to calculate split tensile strength and flexural strength results. Four regression equations like ACI, Ahmed, Gardner and Carino were used for split tensile calculations and ACI, Australian, IS standard equations were used for flexural strength calculations. Normally, the increase in molarity is directly proportional to the compressive strength. The regression coefficient R^2 obtained using ACI Standard was 0.98 to 0.99. In regression analysis, the linear equation based on ACI Standard depicts almost similar values of experimental test results for both split tensile and flexural strength. The coefficient (R^2) value was diverging from 0.9908 to 0.9997. Slag based Geopolymer Concrete attains the target strength of M_{30} with alkaline to binder ratio from 0.3 to 0.9. And with ratio $NaOH/Na_2SiO_3$ 2, and 2.25. Thus, addition of 30% slag with flyash and replacing quarry rock dust for river sand and replacing 30% of recycled coarse aggregate with normal aggregate increases the strength of concrete.

Keywords: Greenhouse emission, sustainable development, waste utilization, geopolymer concrete, molarity, alkaline solution, regression.

1. Introduction

Geopolymer concrete is an innovative material which is produced by the chemical action of inorganic molecules. Geopolymer concrete a way to the sustainable development of concrete Industries. Geopolymer concrete made by the industrial solid waste like as flyash or slag, an alkaline solution, aggregate, sand, water and superplasticizer (Wyom Paul Zakka Wyom Paul Zakka *et al.* 2021). Industrial solid waste like as slag and flyash used as a binding material and alkaline solution used for the activating the industrial solid waste for geopolymerization (Krishnan, S. Karthikeyan *et al.* 2014). The industrial solid waste contains silica and Alumina; geopolymer concrete reduces the carbon footprints due to reducing the use of Portland cement. In 1 ton production of cement produces the one ton of CO2 in the atmosphere (M. I. Abdul Aleem *et al.* 2012). Around 7 to 8% of CO2 produced by the cement production in the world. CO2 is a Greenhouse gas that increases the temperature of the earth (Manvendra

Verma, & Dr Nirendra Dev, 2018). In the development of countries increase the development of the infrastructure that is built by the concrete. So, production of concrete increases day by day due to increase in the demand for infrastructure (Furqan Farooq, Jin Xin *et al.* 2021). Around 120 million tons of flyash produces from the thermal power plant and 12 million tons of slag generated from a steel plant in India. Many valuable cultivated lands used for the disposal of the slag and flyash gases

The selection of source material depends on numerous factors such as availability, price, type of application and particular demand of users (Dr. H. S. Patel, Mr. Bansal R. Patel (2020). The commonly used natural and artificial source materials are kaolinite, clay and fly ash (FA), Ground Granulated Blast Furnace Slag (GGBS), silica fume, metakaolin, rice husk ash, etc. respectively. There are two types of alkaline solutions are used which may be sodium or potassium-based (Numanuddin M. Azad etal,2022) Quarry rock dust is the by-product which is formed during the processing of the granite stones which are broken down into coarse aggregates of different sizes, the powder content left over during the breaking of stones Concrete plays a vital role in the construction industry and on the otherhand, river sand; one of the essential material has become very expensive which is a scarce material. Depletion of sand is a hectic issue due to increased usage of sand in construction (S.Kavipriya *et al.* 2019). QRD, a byproduct of crushing process can be defined as residue, tailing or other non-voluble waste material after the extraction and processing of rocks to form fine particles less than 4.75 mm excellently suits as one of the substitute materials for the natural river sand (Sasi Rekha M, and Sumathy S. R*et al.* 2021).

The Geopolymerization reaction involves three stages such as the dissolution of source materials, reorientation of dissolved particles and formation of a three-dimensional inorganic polymeric binder network (Lloyd N.A. and Rangan B.V., 2010). Development of geopolymer concrete requires suitable mix design to attain its desired strength and workability. Despite of the phenomenal research carried out in the area of geopolymer concrete there is only limited research available on its mix design, a proper and more rational mix design method for GPC is still lacking (Pavithra Parthasarathy *et al.* 2016). For the encouragement of ambient curing condition, some studies were done on Geopolymer Concrete by incorporating the GGBS, Nano-silica and mechanically activated FA (Krishnan *et al.* 2014). The addition of GGBS with Nano-silica ends with the production of more volume of hydrated products (Mallikarjuna Rao *et al.* 2019). It fills the pores present in the Geopolymer Concrete. High calcium content in GGBS ignites the faster Geopolymerization reaction at ambient curing itself. This rapid reaction leads to attaining the 90% of the 28-day compressive strength within 7 days itself (Sasi Rekha M, and Sumathy S.R *et al.* 2021). GGBS (Ground Granulated Blast Slag) is a waste material made in iron or Slag Industries which have a significant impact on Strength and Durability of geopolymer concrete. Geopolymer is generally called 'inorganic polymer', which is ascended a "green" catch by wide conceivable outcomes for amassing efficient supplies for biological, determined and improvement applications (V. Keerthy, Y. Himath Kumar *et al.* 2017). Additionally, extraction of natural aggregates is adversely affecting the natural eco system as the utilisation of concrete is increasing annually. On the other hand, the disposal of construction and demolition (C&D) wastes is also becoming a major environmental issue that has prompted many researchers worldwide to investigate new means of recycling it, with the aim of alleviating the pressure on the scarce landfill space available and also as a means to reduce the current reliance on natural aggregates and minerals (Faiz Uddin Ahmed Shaikh *et al.* 2016). Inferior qualities of concrete like poor fracture toughness, poor resistance to crack propagation and low impact strength can be improved by using fibres in concrete compared to conventional concrete (Numanuddin M *et al.* 2023). In comparison to the most common synthetic reinforcing fibres, natural fibres require less energy to produce and are the ultimate green products (Lloyd, N. *et al.* 2010).

2. Experimental tests and methodology

2.1. Materials

The main source material for the production of Geopolymer Concrete was flyash and slag. The source materials were stimulated to polymerization process through activator solution. The used FA was collected from Mettur thermal power station, Tamilnadu (India) and it has a specific gravity of 3.16 with dark grey in color with fineness 8% and initial setting time 130 minutes. Another source material is slag. It looks like off white in color with a specific gravity of 2.82.

Quarry Rock Dust (QRD) with specific gravity 2.68 and fineness modulus 2.86 confirmed to Zone II was used. Recycled Coarse Aggregate (RCA) with specific gravity 2.61 and fineness modulus 6.32 was used. Coarse aggregate 2.77 and fineness modulus 7.3 was used. Specific gravity of NaOH was 1.47 and Na_2SiO_3 was 1.6.

To achieve the binding property in Geopolymer Concrete, a sodium-based alkaline activator was used. Alkaline activator is the combination of sodium hydroxide and sodium silicate solution. The ratio of sodium silicate solution to NaOH solution was maintained as 2, 2.25 and 2.5 for the preparation of the alkaline solution. And molarity of NaOH was maintained as 16M for all specimens. In this paper, the variation of compressive strength for different alkali activator to source material ratios with 0.3,0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2 have been analyzed. For example, in order to fix alkali activator to source material as 0.4.70% of fly ash with 385Kg/m^3 and slag 30% with 165 Kg/m^3 for M30 was taken. Hence the amount of alkaline liquid was 0.4*550 =220 Kg/m^3. Amount of alkaline activator solution was 220/3.5 = 62.85 Kg/m^3. Amount of sodium silicate solution was 157.15Kg/m^3. Molarity to be used in the concrete is 16M in which 640 gm of NaOH solids per litre. Amount of sodium hydroxide used was 440*62.85 = 27.65 Kg/m^3.Quantity of water = 62.85 - 27.65 = 35.20 Kg/m^3.Extra water with 5% = 0.05 *550 = 27.5Kg/m^3. The

Geopolymer Concrete is somewhat cohesive in nature. So, Poly Carboxylic Ether (PCE) based superplasticizer is used with the specific gravity and pH of 1.1 and 7.5 respectively.

Table 1. Physical properties of Quarry Rock Dust (QRD), Coarse Aggregate (CA), and Recycled Coarse Aggregate (RCA)

Property	Flyash (FA)	Quarry Rock Dust (QRD)	Slag	Coarse Aggregate (CA)	Recycled Coarse Aggregate (RCA)
Specific Gravity	3.16	2.72	2.82	2.80	2.96
Fineness Modulus	2.54	2.50	2.64	7.37	6.97
Water Absorption (%)	0.76	0.60	0.95	0.20	0.60
Bulk Density (loose) (kg/m^3)	1921	1687	1895	1664	1479
Grading zone	-	Zone II as per IS 383(1970): 2002	-	Max. size 20mm	Max. size 20mm

Table 2. Proportions of materials for 1 m^3 of geopolymer concrete with $NaOH/Na_2SiO_3$ ratio = 2

FA	Slag	QRD	CA	RCA	$NaOH/Na_2SiO_3$	Alkali to binder ratio	NaOH		Na_2SiO_3
							Solids	Water	
315	135	568	725	310	2.0	0.3	19.80	25.20	90
315	135	568	725	310	2.0	0.4	26.40	33.60	120
315	135	568	725	310	2.0	0.5	33.00	42.00	150
315	135	568	725	310	2.0	0.6	39.60	50.40	180
315	135	568	725	310	2.0	0.7	46.20	58.80	210
315	135	568	725	310	2.0	0.8	52.80	67.20	240
315	135	568	725	310	2.0	0.9	59.40	75.60	270
315	135	568	725	310	2.0	1.0	66.00	84.00	300
315	135	568	725	310	2.0	1.1	72.60	92.40	330
315	135	568	725	310	2.0	1.2	79.20	100.80	360

Table 3. Proportions of materials for 1 m^3 of geopolymer concrete with $NaOH/Na_2SiO_3$ ratio = 2.25

FA	Slag	QRD	CA	RCA	$NaOH/Na_2SiO_3$	Alkali to binder ratio	NaOH		Na_2SiO_3
							Solids	Water	
315	135	568	725	310	2.25	0.3	18.27	23.26	93.47
315	135	568	725	310	2.25	0.4	24.36	31.02	124.62
315	135	568	725	310	2.25	0.5	30.46	38.77	155.77
315	135	568	725	310	2.25	0.6	36.55	46.52	186.93
315	135	568	725	310	2.25	0.7	42.64	54.28	218.08
315	135	568	725	310	2.25	0.8	48.73	62.03	249.24
315	135	568	725	310	2.25	0.9	54.82	69.79	280.39
315	135	568	725	310	2.25	1.0	60.92	77.54	311.54
315	135	568	725	310	2.25	1.1	67.01	85.29	342.70
315	135	568	725	310	2.25	1.2	73.10	93.05	373.85

2.2. Mix proportion

There is no standard mix design available for the design of Geopolymer Concrete. Only limited research information is available with a new mix design methodology for the FA based Geopolymer concrete (Ferdous M.W *et al.* 2013). The reason is that the mix design of Geopolymer Concrete is tedious and also it depends on numerous factors (Pavithra P *et al.* 2016 Anuradha A *et al.* 2012,). Here, the mix design was developed by a trial-and-error basis. For this research work, the density of concrete was assumed as 2400 kg/m^3.

2.2.1. Calculation of alkaline solution

A molar solution of sodium hydroxide implies concentration in terms of moles/litre. One molar (IM) solution (Nath P. and Sarker P.K. *et al.* 2014) means one mole of a substance per litre of solution A mole means gram molecular weight or molecular weight of a substance, in grams; hence the molecular weight of a chemical is also its molecular weight. The molecule of NaOH consists of one atom each of sodium (Na), Oxygen (O) and hydrogen (H). Their respective atomic weights are Na-23, O-16, H-. So, the molecular weight is 23+16+1=40. Thus 40 grams of NaOH equals One mole of NaOH.10M solution of NaOH contains 400 grams of NaOH. Accordingly, a 16M solution of NaOH was prepared (Nath P. and Sarker P.K. *et al.* 2016). To avoid the effects of unknown contaminants in laboratory tap water, distilled water was used for preparing the activator solution. The solution was prepared one day prior to its use in the casting of specimen to achieve the desired alkalinity (Paramasivan S. *et al.* 2015). Different ratios of sodium silicate to sodium hydroxide were considered as 2,2.25, and 2.5. Ratio of alkali/binder ratio was taken as 0.3 ,0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1

2.2.2. Concrete mixing

For mixing, initially, the fine and coarse aggregates, were kept in saturated surface dry condition (SSD). For the preparation of alkaline solution, the sodium hydroxide solution was prepared first for 16 molarity before 24 hours prior to the time of mixing for complete dissolution of sodium hydroxide flakes into water and also for the liberation of excess heat from the prepared solution due to exothermic reaction. (Manvendra Verma, & Dr Nirendra Dev, 2018). The solutions were prepared with different sodium hydroxide to sodium silicate ratio such as 2.0,2.25, and 2.50. First all ingredients such as flyash, 30% slag, quarry rock dust and coarse aggregate along with 30% recycled coarse aggregate were mixed thoroughly in saturated surface dry condition. Next, the alkaline solution and superplasticizer were gradually added to the dry mix and this wet mixing was continued for about 4-5 minutes.

Table 4. Proportions of materials for 1 m^3 of geopolymer concrete with $NaOH/Na_2SiO_3$ ratio = 2.5

FA	Slag	QRD	CA	RCA	$NaOH/Na_2SiO_3$	Alkali to binder ratio	NaOH		Na_2SiO_3
							Solids	Water	
315	135	568	725	310	2.5	0.3	16.97	21.60	96.43
315	135	568	725	310	2.5	0.4	22.62	28.80	128.58
315	135	568	725	310	2.5	0.5	28.28	36.00	160.72
315	135	568	725	310	2.5	0.6	33.94	43.20	192.86
315	135	568	725	310	2.5	0.7	39.60	50.40	225
315	135	568	725	310	2.5	0.8	45.25	57.60	257.15
315	135	568	725	310	2.5	0.9	50.91	64.80	289.29
315	135	568	725	310	2.5	1.0	56.57	72.00	321.43
315	135	568	725	310	2.5	1.1	62.22	79.20	353.57
315	135	568	725	310	2.5	1.2	67.88	86.40	385.72

Table 5. Compressive Strength of Geopolymer Concrete Specimens for different alkali to binder ratios and $NaOH/Na_2SiO_3$ ratio

Alkali/Binder ratio	Compressive Strength (MPa)			Compressive Strength (MPa)			Compressive Strength (MPa)		
	3 days	7 days	28 days	3 days	7 days	28 days	3 days	7 days	28 days
	Ratio of $NaOH/Na_2SiO_3$ = 2			Ratio of $NaOH/Na_2SiO_3$ = 2.25			Ratio of $NaOH/Na_2SiO_3$ = 2.50		
0.3	4.10	10.25	26.58	4.25	10.41	26.78	4.16	10.21	25.54
0.4	4.87	10.98	26.99	4.94	11.05	27.10	4.81	10.57	26.87
0.5	5.15	11.35	27.54	5.34	11.57	27.78	5.12	10.99	27.15
0.6	5.96	11.87	28.61	6.10	11.99	28.91	5.94	11.24	27.99
0.7	6.35	12.14	29.37	6.57	12.21	29.54	6.15	11.87	28.65
0.8	6.68	12.56	32.35	6.98	12.76	32.95	6.64	12.10	29.54
0.9	7.15	12.99	32.87	7.24	13.11	33.10	7.10	12.79	30.15
1.0	6.34	11.16	31.24	6.94	12.87	32.87	6.51	12.54	29.87
1.1	6.10	10.67	30.85	6.75	12.61	32.71	6.20	12.10	29.34
1.2	5.78	10.34	30.02	6.11	12.20	31.10	5.97	11.97	29.01

2.3. Casting and curing of geopolymer concrete

After the mixing of concrete, Geopolymer Concrete were poured in the corresponding moulds of cubes size 150mm and cylinders of 150 mm diameter with 300mm height, the prisms of size 100mmx100mmx500mm to evaluate the test results of compressive strength, tensile strength, flexure strength respectively (Gunasekera C *et al.* 2015) and the specimens were vibrated on a vibrating table for another 2 minutes. The geopolymer concrete specimens were cast and tested as per Indian Standards IS:516 (1959):2004. (Ferdous M.W *et al.* 2023) Two rest period was given for the specimens. After the rest period specimens were demoulded and allowed for curing at an ambient temperature of 27±2°C. For each test result, the average value of three specimens reported as the final strength (Thirukumaran T *et al.* 2023)

3. Results and discussions

3.1. Compressive strength

The compressive strength of Geopolymer Concrete at 3, 7, and 28 days under ambient curing was calculated. The FA-based Geopolymer Concrete requires longer time to enhance the strength of the concrete. But addition of 30% slag in concrete increases the higher early strength. Around 90% of the 28-day compressive strength can be achieved within 7 days of ambient curing (Mallikarjuna and Kireety, 2019). This development in strength due to the intrusion of slag in concrete which reduces initial as well as final setting time (Pradip Nath and Prabir Kumar Sarker, 2014). Figure 1 represents the compressive strength with flyash based Geopolymer Concrete for the $NaOH/Na_2SiO_3$ ratio 2,2.25, and2.5. Compressive strength increases with increase in $NaOH/Na_2SiO_3$ ratio. From this, it was clearly observed that the rate of attainment of strength increases from 2.0 to 2.25. Beyond 2.5 ratio the compressive strength gets decreased. It was also revealed that the concrete prepared more than 2.25 does not attain higher strength. Also, the concrete specimens were tested with different alkali to binder ratios. The specimens were prepared for different alkali to binder ratios such as 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2. When compared to the test results, compressive strength increases with increase in alkali to binder ratios.

Compressive strength increases from 0.3 to 0.9. Strength results get reduced when the alkali to binder ratio was fixed as 1.0,1.1, and 1.2. It shows that more increase in percentage of NaOH and Na2SiO3 affects the compressive strength of concrete. Test results of 3 days ambient curing with NAOH/Na_2SiO_3 ratio 2 were found as 4.1MPa, 4.87MPa, 5.96MPa, 6.35MPa, 6.68MPa, 7.15MPa, 6.34MPa, 6.10MPa, 5.78MPa for alkali to binder ratios 0.3, 0.4, 0.5, 0.6, 0.7, 0.8,0.9,1.0,1.1,1.2 respectively. With ratio 2.25, it was found as 4.25MPa, 4.94MPa, 5.34MPa, 6.10MPa, 6.57MPa, 6.98MPa, 7.24MPa, 6.94MPa, 6.75MPa, 6.11MPa respectively. And also with ratio 2.5, the compressive strength was found to be 4.16MPa, 4.81MPa, 5.12MPa, 5.94MPa, 6.15MPa, 6.64MPa, 7.10MPa, 6.51MPa, 6.20MPa, 5.97MPa respectively. The strength development in Geopolymer Concrete is mainly depend with the presence of leachable alumino-silicates. The excess leaching of silica at high molarity concentration of sodium hydroxide affects the process of polymerization process which directly affects the strength of polymer concrete. The attainment of strength at 7 days with NaOH/Na_2SiO_3 ratio 2 was 10.25MPa, 10.98MPa, 11.35MPa, 11.87MPa, 12.14MPa, 12.56MPa, 12.99MPa, 11.16MPa, 10.67MPa, 10.34MPa. Also, with NaOH/Na_2SiO_3 ratio 2.25 the strength attainment was 10.41MPa, 11.05MPa, 11.57MPa, 11.99MPa, 12.21MPa, 12.76MPa, 13.11MPa, 12.87MPa, 12.61MPa, 12.20MPa respectively. Strength of the above said specimens were evaluated with different alkali to binder ratios with 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2. Strength of concrete increases with alkali to binder ratios from 0.3 to 0.9. When the ratio increases more than 0.9, the strength of the concrete gets decreased. This indicates that increase in concentration of alkali liquid affects the strength improvement. The strength of concrete in three days was found to be high with higher concentration of NaOH/Na_2SiO_3 ratio (Lloyd, N. and Rangan, B, *et al.* 2015).

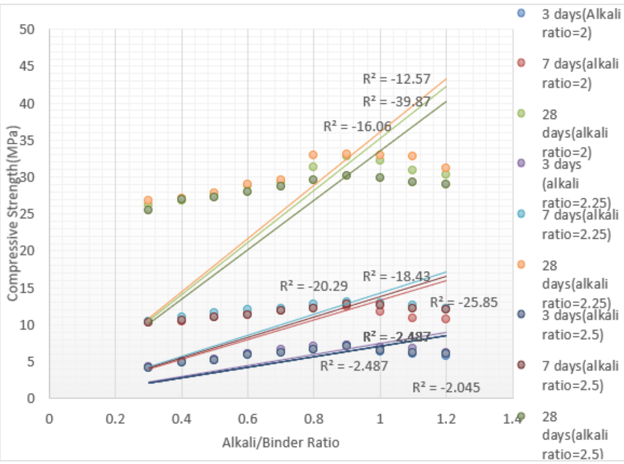


Figure 1. Variations in Compressive Strength with different alkali/binder ratio and NaOH/Na_2Sio_3 ratio

But increase in more volume of sodium hydroxide and sodium silicate also reduces the early strength of concrete (Sasi Rekha M, and Sumathy S.R. *et al.* 2021). The development of high early compressive strength at room temperature is due to the existence of calcium content, silica content in slag and the presence of alumina and silica in FA. The higher strength development in geopolymer concrete is achieved due to the formation of Si-O-Al bonds in the form of sodium aluminate silicate hydrate gel (NASH) and calcium aluminate silicate hydrate gel (CASH).

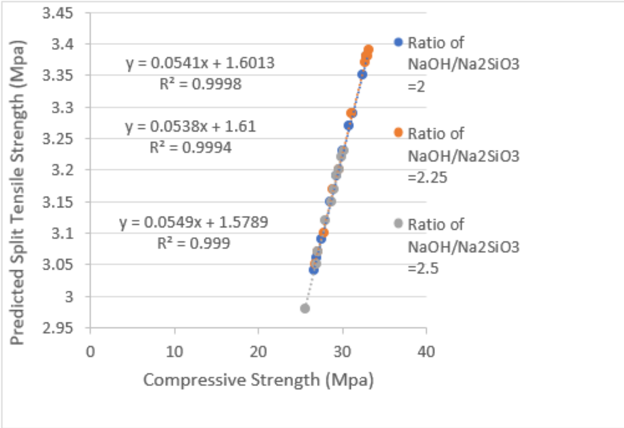


Figure 2. Relation b/w Compressive Strength and Predicted Tensile Strength using ACI, ft = 0.59 fc $^{0.5}$

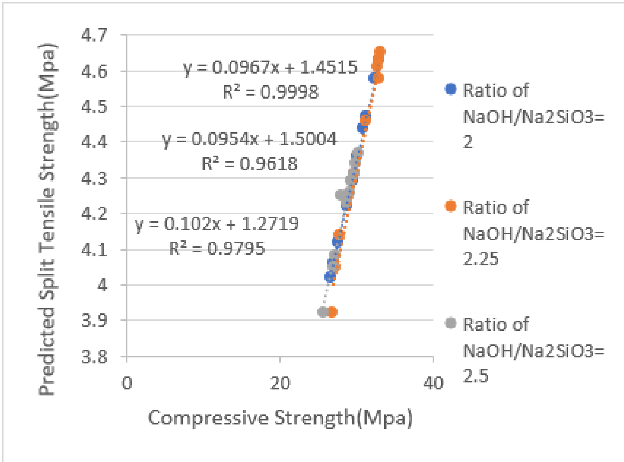


Figure 3. Relation b/w Compressive Strength and Predicted Tensile Strength using Ahmed, ft = 0.462 fc $^{0.66}$

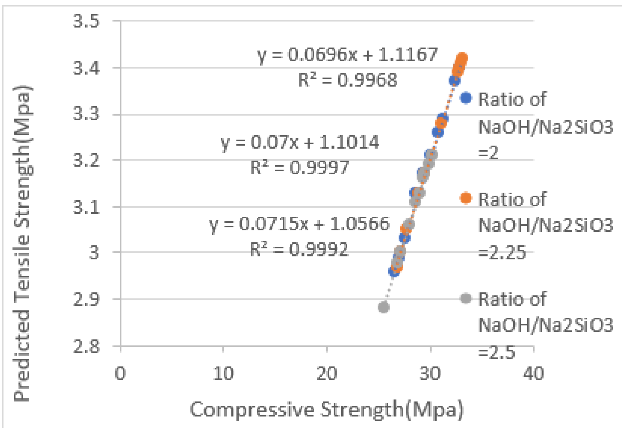


Figure 4. Relation b/w Compressive Strength and Predicted Tensile Strength using Gardner, ft = 0.34 fc $^{0.66}$

3.2. Predicted Compressive Strength and Split Tensile Strength

The relationship between compressive strength and split tensile strength was predicted from the non-linear regression analysis in accordance with power factor to relate the strength parameters of split tensile strength and flexural strength from the experimental source with predicted data (Lloyd, N. and Rangan, B, *et al.* 2015). The coefficient of determination R^2 was determined from the experimental data and regression equation. The value of R^2 was obtained as 0.99 for split tensile equation which explains that 99% of experimental data were correlated with the regression equation and the value of R^2 was 0.98 for flexural strength equation which implies that 98% of experimental data were correlated with the regression equation. The ratio of split tensile strength and compressive strength decreases with increase in compressive strength. From the regression equation obtained the error of percentage between the experimental data and predicted results was less and best accuracy level of results were obtained from the predicted equations (Parbir-Sarker 2008).

Table 6. Predicted Split Tensile Strength of Geopolymer Concrete Specimens for different alkali to binder ratios and $NaOH/Na_2SiO_3$ ratio

Alkali/Binder ratio	Comp Strength (fc) in MPa	Comp Strength (fc) in MPa	Comp Strength (fc) in MPa	Split Tensile Strength (ft) in MPa ACI ft = 0.59 fc $^{0.5}$			Split Tensile Strength (ft) in MPa Ahmed ft = 0.462 fc $^{0.66}$			Split Tensile Strength (ft) in MPa Gardner ft = 0.34 fc $^{0.66}$			Split Tensile Strength (ft) in MPa Carino ft = 0.272 fc $^{0.71}$		
	Ratio of $NaoH/Na_2SiO_3$			Ratio of $NaoH/Na_2SiO_3$			Ratio of $NaoH/Na_2SiO_3$			Ratio of $NaoH/Na_2SiO_3$			Ratio of $NaoH/Na_2SiO_3$		
	2.0	**2.25**	**2.5**	**2.0**	**2.25**	**2.5**	**2.0**	**2.25**	**2.5**	**2.0**	**2.25**	**2.5**	**2.0**	**2.25**	**2.5**
0.3	26.58	26.78	25.54	3.04	3.05	2.98	4.02	3.92	3.92	2.96	2.97	2.88	2.79	2.80	2.71
0.4	26.99	27.10	26.87	3.06	3.07	3.05	4.06	4.05	4.05	2.99	3.00	2.98	2.82	2.83	2.81
0.5	27.54	27.78	27.15	3.09	3.10	3.07	4.12	4.14	4.08	3.03	3.05	3.00	2.86	2.88	2.83
0.6	28.61	28.91	27.99	3.15	3.15	3.12	4.22	4.22	4.25	3.13	3.13	3.06	2.94	2.96	2.89
0.7	29.37	29.54	28.65	3.19	3.19	3.20	4.29	4.31	4.23	3.17	3.17	3.11	2.99	3.00	2.94
0.8	32.35	32.95	29.54	3.35	3.35	3.38	4.63	4.58	4.31	3.37	3.41	3.17	3.21	3.22	3.00
0.9	32.87	33.10	30.15	3.38	3.38	3.39	4.65	4.65	4.37	3.21	3.42	3.21	3.24	3.26	3.05
1.0	31.24	32.87	29.87	3.29	3.29	3.38	4.63	4.63	4.34	3.19	3.40	3.19	3.13	3.24	3.03
1.1	30.85	32.71	29.34	3.27	3.27	3.37	4.61	4.61	4.29	3.26	3.39	3.16	3.10	3.23	2.99
1.2	30.02	31.10	29.01	3.23	3.23	3.29	4.46	4.46	4.26	3.21	3.28	3.13	3.04	3.12	2.97

Table. 7 Relation between Experimental Split Tensile Strength and Compressive Strength of Geopolymer Concrete Specimens for different alkali to binder ratios and $NaOH/Na_2SiO_3$ ratio.

Alkali/Binder ratio	Comp Strength (fc) in MPa	Comp Strength (fc) in MPa	Comp Strength (fc) in MPa	Split Tensile Strength(ft) in MPa	Split Tensile Strength(ft) in MPa	Split Tensile Strength(ft) in MPa
	Ratio of $NaOH/Na_2SiO_3$			Ratio of $NaOH/Na_2SiO_3$		
	2.0	**2.25**	**2.5**	**2.0**	**2.25**	**2.5**
0.3	26.58	26.78	25.54	3.1	3.11	2.97
0.4	26.99	27.10	26.87	3.14	3.15	3.09
0.5	27.54	27.78	27.15	3.17	3.19	3.10
0.6	28.61	28.91	27.99	3.19	3.21	3.12
0.7	29.37	29.54	28.65	3.21	3.23	3.15
0.8	32.35	32.95	29.54	3.27	3.31	3.20
0.9	32.87	33.10	30.15	3.30	3.35	3.23
1.0	31.24	32.87	29.87	3.24	3.31	3.22
1.1	30.85	32.71	29.34	3.20	3.27	3.19
1.2	30.02	31.10	29.01	3.18	3.24	3.17

Predicted split tensile strength was calculated using different equations (Hardjito D. and Rangan B.V*et al.* 2015).

$$\text{ACI, ft} = 0.59\ fc^{0.5}\ \text{MPa} \qquad (1)$$

The above-mentioned equation correlates the relation between compressive strength (fc) and split tensile strength (ft). The equation exhibits almost similar strength to practical test results found at 28 days of ambient curing. The regression coefficient value R^2 lies with coefficient 0.99 value for the test results predicted with $NaOH/Na_2SiO_3$ ratio 2, 2.25 and 2.5. with different alkali to binder ratios 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2. That is 99% of predicted results were correlated with experimental results.

Predicted split tensile was calculated using (Lloyd, N. and Rangan, B, *et al.* 2015)

$$\text{Ahmed, ft} = 0.462\ fc^{0.66}\text{MPa} \qquad (2)$$

The predicted results of tensile strength using this equation shows higher attainment of strength results compared to the experimental test results. The predicted equation depicts the relation between alkaline liquid to binder ratio and ratio of $NaOH/Na_2SiO_3$. Here the regression coefficient value R^2 lies with coefficient 0.96 to 0.99. Hence 96% to 99% of predicted results were correlated with experimental test results.

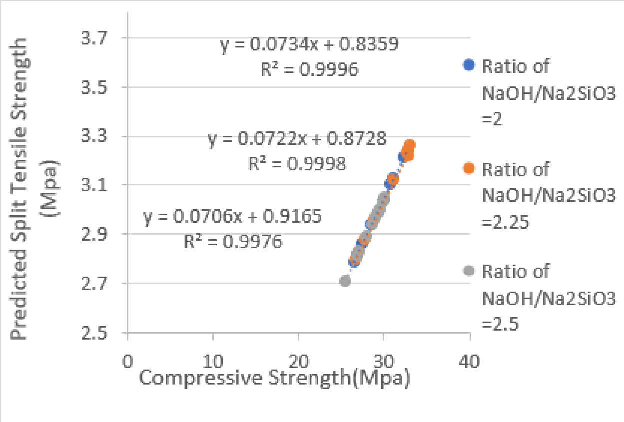


Figure 5. Relation b/w Compressive Strength and Predicted Tensile Strength using Carino, ft = 0.272 fc $^{0.71}$

Predicted split tensile strength was calculated using the equation, (Lloyd, N. and Rangan, B, *et al.* 2015)

Gardner, ft = 0.34 $fc^{0.66}$Mpa (3)

The predicted correlated results were almost similar to test results. Almost the predicted results of ACI equation and gardner were similar. The regression coefficient lies by 0.99 with all $NaOH/Na_2SiO_3$ ratios.

Predicted split tensile was calculated using, (Lloyd, N. and Rangan, B, *et al.* 2015)

Carino, ft = 0.272 $fc^{0.71}$MPa (4)

This equation also results with similar test results highly correlated with predicted results. The regression coefficient lies by 0.99, with 99% of accuracy correlated with experimental test results.

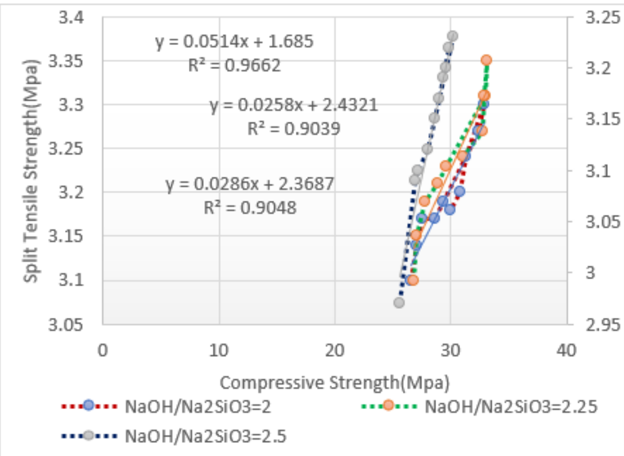


Figure 6. Relation b/w compressive strength and experimental tensile strength

3.3. Relation between flexural strength and compressive strength

The Figure 7 represents the relation between flexural strength and compressive strength using Australian Standards with the equation, (Hardjito D. and Rangan B. V *et al.* 2015).

fcr = 0.6 $fc^{0.5}$Mpa (5)

Where, fcr is the mean flexural strength at 28-days ambient temperature curing, and fc denotes the average compressive strength at 28-days. The linear regression line is made between the two variables that expressing a R^2 value of 0.92 to 0.99.

The recommended mean flexural strength "fcr" associated with compressive strength "fc" as per ACI Standards, (Hardjito D. and Rangan B. V *et al.* 2015).

fcr = 0.85fc $^{0.5}$ MPa (6)

Indian Standard of IS 456:2000 derived an equation (7) to evaluate the flexural strength "fcr" as follows (Hardjito D. and Rangan B. V *et al.* 2015).

fcr = 0.8$fc^{0.5}$MPa (7)

The flexural strength of Geopolymer Concrete cured at room temperature found by experimental results are reported higher value than the codal specifications developed for conventional concrete (S. Kavipriya *et al.* 2021) By referring the equations and experimental test results, the equation used to estimate mean flexural strength recommended by ACI can be used for ambient cured Geopolymer Concrete with marginal factor of safety.

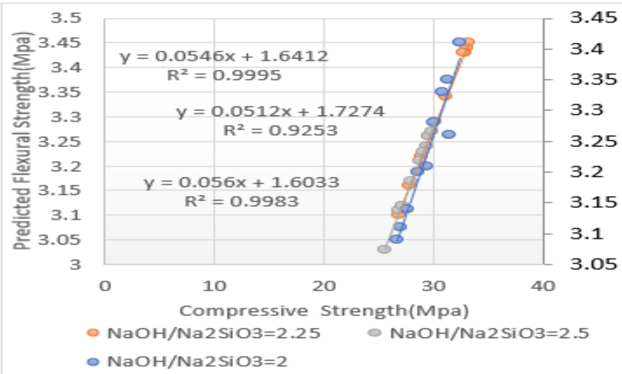


Figure 7. Relation b/w Compressive Strength and Predicted Flexural Strength using Australian Standards fcr = 0.6 fc $^{0.5}$

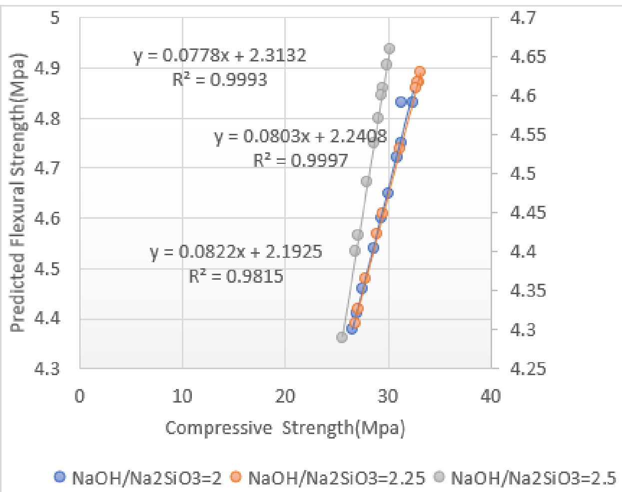


Figure 8. Relation b/w Compressive Strength and Predicted Flexural Strength using ACI, fcr= 0.85 fc $^{0.5}$

Table.8 Relation between Predicted flexural Strength, Experimental results and Compressive Strength of Geopolymer Concrete Specimens for different alkali to binder ratios and NaOH/Na_2SiO_3 ratio

Alkali/Binder ratio	Comp Strength (fc) in MPa	Comp Strength (fc) in MPa	Comp Strength (fc) in MPa	Flexural Strength (fcr) in MPa Australian Standards fcr = 0.6 fc $^{0.5}$			Flexural Strength (ft) in MPa ACI fcr= 0.85 fc $^{0.5}$			Flexural Strength (ft) in MPa IS fcr = 0.8 fc $^{0.5}$			Experimental Results of flexural Strength (ft) in MPa		
	Ratio of NaOH/Na_2SiO_3			Ratio of NaoH/Na_2SiO_3			Ratio of NaoH/Na_2SiO_3			Ratio of NaoH/Na_2SiO_3			Ratio of NaoH/Na_2SiO_3		
	2.0	2.25	2.5	2.0	2.25	2.5	2.0	2.25	2.5	2.0	2.25	2.5	2.0	2.25	2.5
0.3	26.58	26.78	25.54	3.09	3.10	3.03	4.38	4.39	4.29	3.60	4.13	4.04	4.64	4.65	4.54
0.4	26.99	27.10	26.87	3.11	3.12	3.11	4.41	4.42	4.40	4.15	4.16	4.14	4.67	4.67	4.66
0.5	27.54	27.78	27.15	3.14	3.16	3.12	4.46	4.48	4.42	4.19	4.21	4.16	4.72	4.74	4.68
0.6	28.61	28.91	27.99	3.20	3.22	3.17	4.54	4.57	4.49	4.27	4.30	4.23	4.81	4.81	4.76
0.7	29.37	29.54	28.65	3.21	3.26	3.21	4.60	4.61	4.54	4.33	4.34	4.28	4.87	4.87	4.81
0.8	32.35	32.95	29.54	3.26	3.44	3.26	4.83	4.87	4.61	4.55	4.59	4.34	5.11	5.16	4.89
0.9	32.39	33.10	30.15	3.41	3.45	3.29	4.83	4.89	4.66	4.55	4.60	4.39	5.12	5.17	4.94
1.0	31.24	32.87	29.87	3.35	3.43	3.27	4.75	4.87	4.64	4.47	4.58	4.37	5.03	5.15	4.91
1.1	30.85	32.71	29.34	3.33	3.43	3.24	4.72	4.86	4.60	4.44	4.57	4.33	4.99	5.14	4.87
1.2	30.02	31.10	29.01	3.28	3.34	3.23	4.65	4.74	4.57	4.38	4.46	4.30	4.93	5.01	4.84

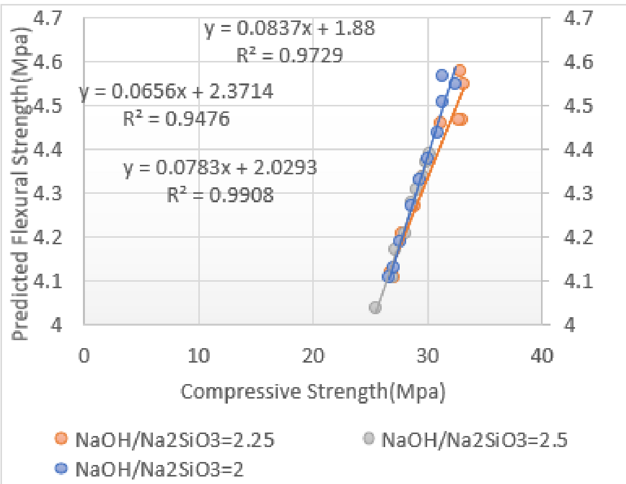


Figure 9. Relation b/w Compressive Strength and Predicted Flexural Strength using IS, fcr= 0.8 fc $^{0.5}$

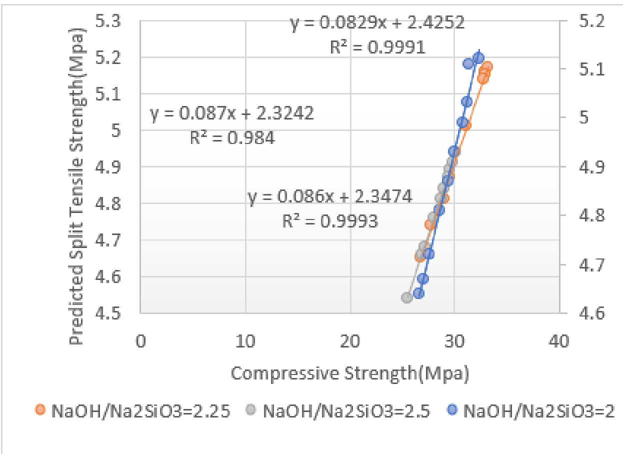


Figure 10. Relation b/w Compressive Strength and Experimental Flexural Strength results

The correlated linear regression equation for Australian The regression equation using ACI standards shows coefficient R^2 value with 0.98 to 0.99. In this equation,"y" represents the flexural strength of geopolymer concrete specimens and "x" represents the compressive strength at 28 days of curing at ambient temperature. Thus, the value accuracy lies between 98% to 99%. The experimental results were almost similar to the equation of ACI standards. Standards shows coefficient R^2 value with 0.92 to 0.99. is made between the two variables that expressing a R2 value of 0.92 to 0.99. In this equation,"y" represents the flexural strength of geopolymer concrete specimens and "x" represents the compressive strength at 28 days of curing at ambient temperature. Thus, the value accuracy lies between 92% to 99%. The regression equation using IS standards shows coefficient R^2 value with 0.94 to 0.99. In this equation,"y" represents the flexural strength of geopolymer concrete specimens and "x" represents the compressive strength at 28 days of curing at ambient temperature. Thus, the value accuracy lies between 94% to 99%. The results compared with experimental results shows less values. But comparatively higher results compared to ACI standard regression equation correlated values. Compared to three regression equations, the predicted flexural strength results of Australian standards show less value of results with less accuracy compared to other equations. The results compared with ACI standards shows almost similar results to experimental values. Compared to split tensile strength results, flexural strength also increases by increasing the alkalinity ratio. But more than increase in 0.9 of alkalinity ratio reduces the polymerization process in concrete. Alkalinity ratio with 1.0 ,1.1 and1.2 reduces the strength of concrete. Similarly, as such in split tensile ratio of NaOH/Na_2SiO_3 with 2.0 and 2.25 shows excellent strength results but increase in ratio with 2.5 reduces the strength of concrete. The regression coefficient R^2 values of experimental test results lie with 0.98 to 0.99. Thus, accuracy results with 98% to 99% in experimental results of flexural strength.

4. Conclusion

This paper was presented to study the effect of alkaline liquid to binder ratio and the ratio of $NaOH/Na_2SiO_3$ ratio in geopolymer concrete to develop an ecofriendly sustainable green concrete by reducing the consumption of cement in construction.

From the experiment results, the following suggestions were concluded

In FA and slag based Geopolymer Concrete, the incorporation of calcium in slag support to enhance the early strength of concrete. The 3-days and 7-days strength were around 55-70% and 85-95% of 28 days compressive strength were achieved with alkaline liquid to binder ratio 0.3 to 0.9. But the strength values get reduced for the alkalinity liquid to binder ratio for 1.0,1.1 and1.2.

The Geopolymer Concrete made with alkalinity liquid to binder ratio more than 0.9 reduces the early strength and final strength of concrete. Thus, addition of more flyash and alkaline liquid affects the process of geopolymerization, thus reducing formation of NASH Gel and CASH gel with Si-O-Al bond formation.

The physical strength of Geopolymer Concrete generally increases with increasing the ratio of $NaOH/Na_2SiO_3$ ratio. When the ratio of sodium hydroxide to sodium silicate increases, the strength of concrete gets increased. By fixing the ratio with 2,2.25 increases the strength of concrete at 3 days,7 days and 28 days. But more than increase in ratio with 2.25 reduces the strength of concrete, thus ratio of 2.5 reduces the early strength and final strength attained in geopolymer concrete.

The correlated regression equation using ACI Standard for the prediction of split tensile strength and flexural strength gives conservative results for ambient cured Geopolymer Concrete compared with experimental results.

The regression coefficient R^2 obtained using ACI Standard was 0.98 to 0.99. More accuracy values were predicted for flexural strength using ACI Standard equation compared to Australian Standard, and Indian Standard.

More accurate results were predicted in regression analysis for split tensile strength results using ACI standards compared to other equations Ahmed, Gardner and carino.

In regression analysis, the linear equations were well suited to the experimental results obtained from the split tensile and flexural strength test results. The coefficient (R^2) value was diverging from 0.9908 to 0.9997.

With regression analysis, the 28-days splitting tensile and flexural strengths for various molarities of Geopolymer Concrete ranged between 2.96 - 4.65MPa and 3.03 – 5.12MPa respectively by using linear regression equations with compressive strength as derivation factor.

It was clearly described that Geopolymer Concrete attains the target strength of M30 with alkaline to binder ratio from 0.3 to 0.9. And with ratio $NaOH/Na_2SiO_3$ 2, and 2.25. Addition of 30% slag with flyash and replacing quarry rock dust for river sand and replacing 50% recycled coarse aggregate with normal coarse aggregate increases the strength of concrete.

From this study, slag based Geopolymer Concrete production should be increased to minimize the effect of carbondioxide emission. And industrial waste products such as quarry rock dust and demolition waste like Recycled coarse aggregate can be utilized in slag concrete production.

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Conflict of interest

There is no conflict of interest.

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